Radiation and Environmental Biophysics (2022) 61:597–608
https://doi.org/10.1007/s00411-022-00993-3

REVIEW

The status of natural radioactivity in Nigerian environments

Michael A. Olatunji[1,2] · Mayeen U. Khandaker[3,4] · Victor U. J. Nwankwo[2] · Abubakr M. Idris[5,6]

Received: 26 January 2022 / Accepted: 3 September 2022 / Published online: 29 September 2022

Abstract

Proper documentation of baseline radiation data of different environments is an important step toward adequate environmental monitoring, and it provides quick means to quantitatively check and determine possible radionuclide contamination by anthropogenic sources. Besides, such documentation is useful for decision making processes, assessment of dose rates to the public, epidemiological studies, and environmental regulations. This review summarizes the results of studies conducted on radioactivity in Nigerian environments. For most soil samples, the levels of radioactivity are well within the world averages of 33, 45, and 420 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively. Other soil samples from regions such as Abeokuta in the southwest, and Jos in the northcentral have been described as high background radiation areas with radioactivity values comparable with those obtained from known high background radiation areas such as the Odisha (formerly Orissa) coast in India (with values reported as 350, 2,825, and 180 Bq kg^{-1} for ^{238}U/^{226}Ra, ^{232}Th, and ^{40}K, respectively). In some parts of Nigeria, surface and underground water sources used for drinking and other purposes also present elevated levels of ^{226}Ra above the world range of 0.01 to 0.1 Bq l^{-1} and the tolerable levels recommended by the World Health Organization and U.S. Environmental Protection Agency. Corresponding radiation doses due to measured radioactivities from different environments were estimated and compared with those reported in similar studies around the world. More so, the human and environmental health hazards that might be associated with the reported radioactivity in different environmental settings are discussed. The present report is expected to support authorities in developing appropriate regulations to protect the public from radiation exposure arising from environmental radioactivity. The report also examines other areas of consideration for future studies to ensure adequate radiation monitoring in Nigeria.

Keywords NORM · TENORM · Nigerian environment · Background radiation · Radiation dose

Introduction

In general, the background radiation dose in any human environment is due to contribution from both natural and anthropogenic sources. The background level from natural sources depends on the geological composition, mineral composition, and the presence of U, Th, and K in rocks and soils of a particular place (Abba et al. 2017; Shuaibu et al. 2017). In contrast, certain human activities which may result in environmental contamination by radionuclides account for anthropogenic sources. In Nigeria, apart from exposure due to natural radioactivity in soil and rock, human activities such as extraction and reprocessing of crude oil, solid mineral mining, and milling also contribute a significant portion to the total radiation level in the environment (Alatise et al. 2008). Although natural background radiation levels for most of the regions have not yet been established, some notable efforts have been made in the last two decades of

✉ Mayeen U. Khandaker
mu_khandaker@yahoo.com; mayeenk@sunway.edu.my

1 Department of Physics, Faculty of Science, University of Medical Sciences, Ondo, Nigeria

2 Space, Atmospheric Physics & Radio Wave Propagation Laboratory, Department of Physics, Anchor University Lagos, Lago, Nigeria

3 Centre for Applied Physics and Radiation Technologies, School of Engineering and Technology, Sunway University, 47500 Selangor, Malaysia

4 Department of General Educational Development, Faculty of Science and Information Technology, Daffodil International University, DIU Rd., Dhaka 1341, Bangladesh

5 Department of Chemistry, College of Science, King Khalid University, Abha 62529, Saudi Arabia

6 Research Center for Advanced Materials Science (RCAMS), King Khalid University, Abha 61431, Saudi Arabia

environmental radioactivity assessment (Abba et al. 2017). Despite of these activities, however, systematic data on natural and artificial radioactivity in Nigeria is scarce and, therefore, there is a need for the creation of a scientific database of levels of radioactivity in Nigeria. Nowadays, human radiation exposure is increasingly considered in decision making processes and for the formulation of sound environmental policies (Guidotti et al. 2015). While Lagos state is known as the center of significant industrial activities in Nigeria, different industrial activities are currently spreading to other parts of the country. This development suggests that in the next few years, many other states in Nigeria may witness the growth of various sorts of industries. Presently, there are concerns regarding the environmental implications of mining activities spreading across the northcentral and parts of the southwestern states of the country (Oramah et al. 2015; Omotehinse and Ako, 2019). Consequently, there is an urgent need to gather information on radiation levels across Nigeria into a single document for easy access. Such data should provide a valuable and useful reference when standard and regulatory control actions on radiation protection are to be established (Doyi et al. 2017). Note that current efforts of the Nigerian government are geared toward the deployment of a pioneer nuclear power plant to cover the energy need of the country within the next few years, which in turn may impact the environmental radioactivity levels when in operation (Aliyu et al. 2013).

The main objective of the present study is, therefore, to concentrate different studies on natural environmental radioactivity levels for different regions in the country into single radiation-data report for easier accessibility by decision-makers and for the general public. A report of this kind is anticipated to support in developing a holistic view of the current situation of human exposure due to environmental radioactivity in Nigeria. This should support the development and implementation of adequate guidelines towards the use of radioactive materials and other practices that may enhance background radioactivity levels in the environment. The report may also serve as a useful reference in the design and development of specific regional surveys where there are enhanced radioactivity levels.

Methods of radioactivity measurements and associated radiological hazard indices

For the purpose of environmental radiation monitoring, quantification of radioactivity levels in environmental materials is pivotal. In achieving this, different techniques/methods can be employed, depending on the type of radiation emitted by the radionuclides present. Most of the authors of studies reviewed in the present paper employed the use of the gamma-ray spectrometry method involving high purity germanium (HPGe) detectors or thallium-activated sodium iodide (NaI(Tl)) detectors. Such detectors allow measurement of very low concentrations of naturally occurring radioactive materials (NORMs). Normally, the radionuclides of interest (e.g., ^{238}U, ^{232}Th) are quantified based on the gamma-rays emitted from their short-lived progeny, or on the gamma-rays emitted by ^{40}K (Olatunji et al. 2014). Table S1 presents the main radionuclides of interest and their gamma-emitting daughters investigated by various authors of the reviewed literature.

Whether by use of HPGe or NaI(Tl) detectors, the radioactivity concentration in any given material, neglecting several corrections such as coincidence summing and gamma-ray attenuation, etc., can be obtained from Eq. (1) (Khandaker et al. 2012; 2013; Asaduzzaman et al. 2015):

$$A = \frac{N}{\varepsilon_\gamma I_\gamma m t}(\mathrm{Bq/kg}), \tag{1}$$

where A is the radioactivity concentration in the sample, N is the net counts or counting area under a photopeak, ε_γ is the efficiency of the detector for particular gamma-ray energy, m is the mass of the sample, I_γ is the branching ratio or intensity of the emitted gamma-ray, and t is the counting time.

The radioactivity concentration in any material and the time of exposure determines the radiation dose received by an individual. Once the radioactivity concentration in any material is quantified, radiation indices describing the level of exposure and assessing the extent of any radiological health hazards can be evaluated. The most common of these indices is known as radium equivalent activity ($\mathrm{Ra_{eq}}$). This activity is defined as the weighted sum of activities in NORMs based on the assumption that 370 Bq kg^{-1} of ^{226}Ra, 259 Bq kg^{-1} of ^{232}Th, and 4,810 Bq kg^{-1} of ^{40}K produce the same gamma-ray dose rate (Oyeyemi and Aizebeokhai 2015). This is reflected in Eq. (2) (OECD 1979; UNSCEAR 1982):

$$\mathrm{Ra_{eq}} = A_{\mathrm{Ra}} + 1.43A_{Th} + 0.077A_K, \tag{2}$$

where A_{Ra}, A_{Th}, and A_K represent radioactivity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, respectively. The radium equivalent activity for building materials has recommended reference value of 370 Bq kg^{-1}, and 740 Bq kg^{-1} for materials used in road construction (Isinkaye 2008).

The outdoor absorbed dose rate (D_{out}, $nGy\ h^{-1}$) in air at 1 m above the ground surface is another useful parameter for estimating the level of external exposure. By definition, absorbed dose is defined as the energy deposited in matter by ionizing radiation per unit mass (Ademola and Atare 2010). Following the standard guidelines of UNSCEAR (2000), D_{out} can be calculated for natural radionuclides using the conversion factors ($4.62 \times 10^{-10} Gyh^{-1}/Bgkg^{-1}$ for ^{226}Ra, $6.04 \times 10^{-10} Gyh^{-1}/Bqkg^{-1}$ for ^{232}Th, and

$0.417 \times 10^{-10} Gyh^{-1}/Bqkg^{-1}$ for ^{40}K). Consequently, Eq. (3) is used for external absorbed dose rate calculation (UNSCEAR 1988; 2000):

$$D_{\text{out}}\left(nGyh^{-1}\right) = 0.462A_{\text{Ra}} + 0.604A_{\text{Th}} + 0.042A_K. \quad (3)$$

The average global terrestrial radiation dose rate has been estimated at 57 nGyh^{-1} while the country average ranged from 24 to 160 nGyh^{-1} (UNSCEAR 2000). To assess the biological effects of ionizing radiation, the absorbed dose rate in air is usually related to effective dose. For external exposure, an outdoor annual effective dose (AED_{out}) has been introduced, to calculate the dose received by an individual due to the presence of radionuclides in the environment (e.g., in soil and mineral ores, water, and building materials). The outdoor annual effective dose received by an individual free-in-air resulting from the external absorbed dose rate can be obtained from Eq. (4) (UNSCEAR 1982, 2000):

$$AED_{\text{out}} = TfQD_{\text{ext}}, \quad (4)$$

where the AED_{out} is typically given in terms of Sievert per year ($Sv\ y^{-1}$), T is the annual exposure time (given as 8,760 h y^{-1}), f is the occupancy factor that corrects for the average time an individual is exposed to outdoor radiation, and Q is the conversion factor of external absorbed dose rate in the air to effective dose rate in human. The values of these factors have been set by international regulatory bodies, so that dose estimation is harmonized all over the world. According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2000), 0.2 is set as the value for the outdoor occupancy factor (indicating approximately an outdoor exposure of 5 hours per day), 0.7 Sv Gy^{-1} is the conversion factor for external gamma irradiation (which converts the external outdoor absorbed dose rate to outdoor effective dose rate), respectively. However, it is important to note that the occupancy factor can change depending on individual lifestyle. For instance, outdoor exposure to radiation from radionuclides in the soil can be up to about 10 h per day for West African farmers, where virtually all agricultural activities are manually practiced (Jibiri et al. 2009a). Sometimes, incorporation (by inhalation or ingestion) of radionuclides in dust particles from environmental samples such as soil or building materials is inevitable, due to the nature of activities involved with these materials. In such a case, the resulting effective dose from internal exposure can also be calculated for radiological hazard purposes. The worldwide average annual effective dose is estimated as 0.45 mSv y^{-1} (UNSCEAR 1993).

Consequently, the indoor gamma dose rate (D_{in}) and the corresponding annual effective dose (AED_{in}) due to the exposure of gamma-rays emitted from the radionuclides in the soil or other building materials can also be calculated, just as is done above. Equation (5) is recommended for calculation of the indoor absorbed dose rate (D_{in}) (UNSCEAR 1988; 2000):

$$D_{in}\left(nGyh^{-1}\right) = 0.92A_{Ra} + 1.1A_{Th} + 0.080A_K. \quad (5)$$

Similarly, the indoor annual effective dose (AED_{in}) can be calculated by the following equation:

$$AED_{in} = TyQD_{in}, \quad (6)$$

where y represents the indoor occupancy factor that corrects for the average time by an individual spent indoors, while the other quantities retain their usual meanings. In this case, the value of 0.8 for the indoor occupancy factor has been set by international regulatory bodies, assuming that 80% of a person's time is spent indoors. Note again, this is an average time spent; differences may occur depending on individual lifestyle.

Apart from external exposure, internal exposure to natural radionuclides is unavoidable due to consumption of water. Hence, annual effective dose (AED_{ing}) due to ingestion of radionuclides in drinking water is usually calculated following the following equation (UNSCEAR 2008):

$$AED_{\text{ing}} = \sum A_c A_i C_f, \quad (7)$$

where A_c represents the activity concentration of any radionuclide in water, A_i is the annual intake of drinking water and C_f is the ingestion dose conversion factor for the radionuclide, which depends on the particular radionuclide and the age of the individual ingesting the radionuclide.

The reference value recommended by the European Union for the annual effective dose is 1 mSv y^{-1} and as proposed by ICRP, 1 Sv of effective dose roughly implies a 5% probability of dying from cancer and/or developing some heritable effects at some time in life (ICRP 2007).

The radiological suitability of any material used for building purposes is usually assessed using the external hazard index (H_{ex}). For natural radiation, the external hazard index is expressed by the following equation (OECD 1979):

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810}. \quad (8)$$

The external hazard index can also be obtained from the expression for Ra_{eq} assuming that its maximum allowed value corresponds to the upper limit of $\text{Ra}_{\text{eq}}\left(370\text{Bq kg}^{-1}\right)\left(i.e. H_{ex} = \frac{\text{Ra}_{\text{eq}}}{370}\right)$, so that the annual dose rate does not exceed 1.5 mSy y^{-1}. To limit the external gamma radiation dose from building materials to 1.5 mSy y^{-1} so that radiation hazard is negligible, the external hazard index should obey the criterion of $H_{ex} \leq 1$.

Furthermore, the internal hazard index is the criterion for assessing radiation hazard due to internal exposure (via the

inhalation pathway) to gaseous radon and thoron, the decay products of ^{226}Ra and ^{228}Ra, as well as the internal exposure (via ingestion of foodstuffs) to alpha and beta particles emitting short-lived progeny of ^{226}Ra and ^{228}Ra, and singly occurring beta emitter ^{40}K. The internal hazard index (H_{in}) due to NORMs is quantified using the following equation (Beretka and Matthew 1985):

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{\mathrm{Th}}}{259} + \frac{A_K}{4810}. \tag{9}$$

If the maximum radioactivity concentration of ^{226}Ra is half of that of the permissible limit, then H_{in} will be less than unity. For the safe use of a material in the construction of dwellings, this index should be, $H_{in} \leq 1$.

Besides this, the gamma index (I_γ) or representative index is used to correlate the annual dose rate due to the excess external gamma radiation caused by surface contamination. As a screening tool, it helps in identifying materials that may pose danger to human health when used in the construction of the building (Jibiri et al. 2009a; ITB/CLOR 1995). The gamma index, as proposed by the European Commission, is given in the following equation (EC 1999):

$$I_\gamma = \frac{A_{\mathrm{Ra}}}{300} + \frac{A_{\mathrm{Th}}}{200} + \frac{A_K}{3000}. \tag{10}$$

The value of $I_\gamma \leq 1$ corresponds to an annual effective dose of less than or equal to 1 mSv y^{-1}, while $I_\gamma \leq 0.5$ corresponds to an annual effective dose less than or equal to 0.3 mSv y^{-1}.

The excess alpha radiation due to radon inhalation from building materials is estimated by the alpha index (I_α) (Eq. (11) (EC 1999):

$$I_\alpha = \frac{A_{\mathrm{Ra}}}{200}. \tag{11}$$

The recommended exempted upper level of ^{226}Ra is set between 100 Bq kg^{-1} and 200 Bq kg^{-1}, respectively. The implication is that a radium concentration higher than 200 Bq kg^{-1} in building materials may cause an indoor radon concentration exceeding 200 Bq m^{-3}, while concentration below 100 Bq kg^{-1} implies an indoor radon concentration well below 200 Bq m^{-3}. The recommended upper limit for ^{226}Ra for which $I_\alpha = 1$ is 200 Bq kg^{-1} (ICRP 1994).

The annual gonadal dose equivalent (AGDE) which represents a yearly dose received by gonads, bone marrows and bone surface cells due to specific activities of ^{238}U, ^{232}Th, and ^{40}K (UNSCEAR 1998), can be calculated using the following equation (ICRP 1991; UNSCEAR 1988):

$$\mathrm{AGDE} = 3.09A_{\mathrm{Ra}} + 4.18A_{\mathrm{Th}} + 0.314A_K. \tag{12}$$

The world average value of AGDE for soil is 0.30 mSv y^{-1} (Ademola 2008). In addition to the AGDE, the excess lifetime cancer risk (ELCR) is estimated from the annual effective dose by Eq. (13) (ICRP 2007):

$$\mathrm{ELCR} = \mathrm{AED_{in}} \times A_{\mathrm{lf}} \times R_f, \tag{13}$$

where A_{lf} and R_{f} represent the average lifetime (70 y) and detriment-adjusted nominal cancer risk coefficient (5.5×10^{-2} Sv^{-1}) for public exposure, respectively (ICRP 2007).

For most of the studies on environmental radioactivity in Nigeria, the aforementioned radiological hazard indices have been estimated and their corresponding health impacts assessed. In the present paper, reports of studies considered most important were selected which cover all the regions in Nigeria where higher radioactivity levels are known or have been suspected due to human activities. The results of review conducted on various studies are summarized in Tables (S2–S7).

Radioactivity levels in soil and other environmental settings

According to the Soil Science Society of America, soils are complex mixtures of minerals, water, air, organic matter, countless organisms, and decaying remains of once-living creatures. Soil is formed at the surface of the land and can be considered the 'skin of the earth'. It is very important to live on earth, as all the essentials for man's survival, except air, come from the soil. Furthermore, soil occupies the space in which humans exercise their activities and from which they derive the essential necessities for survival (Ajayi et al. 2008). Considering the central role of soil on the continuity of life on earth, the determination of soil radioactivity is critical because it helps in understanding the distribution and behavior of radionuclides in the environment where humans live. From the radiation protection point of view, the soil is the main source of continuous radiation exposure to humans, and also the medium of migration and transfer of radionuclides to biological systems (Doyi et al. 2017). As a result, estimation of the total absorbed dose from exposure pathways is not complete without consideration of soil. Soil background radioactivity levels may vary from place to place depending on the geological features of the considered area. Rocks are very important in this regard because they form the basic material of soil. Consequently, the types of rock determine the level of radioactivity in soil. Deposition of mineral resources such as fertilizers in the subsurface layers of soil can also be responsible for varying levels of soil background radioactivity. Furthermore, contamination due to disasters following natural processes (such as volcano eruptions and landslides) may also be responsible for elevated background radioactivity levels measured in some

soils and environmental samples across the world. Because the evaluation of radioactivity levels in soils, rocks, water, and other environmental samples, is very crucial for environmental health safety. The radioactivity levels in Nigeria are reviewed here including various reports on measurements that have been carried out in soils, rocks, mineral materials, water, exploration/extraction process and building materials, since the time when radiation protection activities were launched in the country.

Radioactivity levels measured in soils, water, and sediments

Attempts have been made here to identify the most relevant studies conducted on the measurement of terrestrial background radioactivity levels in normal soil, water, and sediments obtained from different regions of Nigeria. The results obtained in these studies and their associated radiological hazard indices are summarized in Tables S2–S4.

As revealed in the tables, the background radiation levels in normal/undisturbed soil, water and sediment samples across the country are mostly low and fall within those typical for normal background radiation areas (Obed et al. 2005; Ajayi 2008; 2009; Amakom and Jibiri 2010; Eke et al. 2015; Isola et al. 2015). However, there are a few exceptions where high radioactivity levels were recorded, i.e., in soils of the Owo area of Ondo and the Abeokuta area of Ogun in the southwest region of Nigeria, and soils of industrial districts of the Federal Capital city Abuja and Jos-Plateau in the northcentral region (Fig. 1) (Aladeniyi et al. 2019). At these locations the radioactivity levels are higher than the world average values of 33, 45, and 420 Bq kg^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K, respectively, reported by the United Nations Scientific Committee for the Effects of Atomic Radiation (UNSCEAR 2000). The sediment samples from Oguta Lake in the south-east of Nigeria and from Bonny estuary in the Niger Delta show also radioactivity levels higher than the global average levels of 25, 25, and 50 Bq kg^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K, respectively, reported by UNSCEAR (1998). Similarly, the radioactivity levels of some water sources available for drinking and other domestic purposes in some localities warrant concern. Different national and international bodies such as the World Health Organisation (WHO) have introduced permissible levels of 1.0, 0.1, and 10 Bq l^{-1} for ^{226}Ra, ^{228}Ra, and ^{40}K, respectively, for drinking water (WHO 2008, 2011), and the U.S. Environmental Protection Agency recommended maximum levels of 15 pCi L^{-1} (0.55 Bq l^{-1}) for alpha emitters, 4 mrem per year (40 µSv per year) for beta and photon emitters, 5 pCi L^{-1} (0.18 Bq l^{-1}) for radium ($^{226}Ra/^{228}Ra$), and 30 µg L^{-1} (0.74 Bq l^{-1}) for uranium in drinking water (USEPA 2000). These values are lower than the radioactivity levels of natural radionuclides

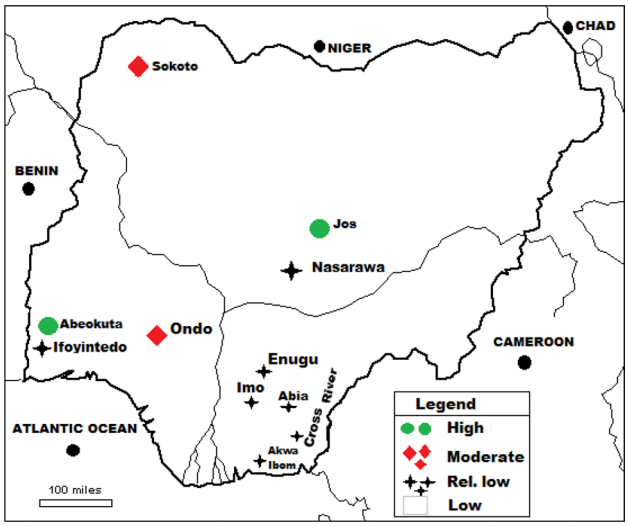

Fig. 1 Map of Nigeria showing background radioactivity distribution patterns. The classification of "high", "moderate", "rel. low", and "low" is based on ^{226}Ra, ^{238}U, and ^{232}Th radioactivity concentrations measured in samples of rocks, soils, or sediments as reported in the literature

(^{226}Ra in particular) reported for drinking water samples collected from the Federal Capital city Abuja in the northcentral region of Nigeria (Umar et al. 2012), and for the Niger Delta in the oil-rich southern region (Agbalagba and Onoja 2011), Ile-Ife in Osun state (Tchokossa et al. 1999) and some parts of Ogun state (Ajayi and Achuka 2009). The elevated levels of radionuclides in the soil and drinking water in the abovementioned areas are an indication of contamination which may be due to anthropogenic activities in those areas, where these samples were collected. Because some of the authors of the reviewed studies have raised concerns, further studies are encouraged on the plant, animal and human radiation exposure due to the usage of soil, sediment and water in the mentioned areas.

Measured radioactivity in mineral materials

Through efforts of numerous research groups, radiation data have been generated for a few mineral materials and chemical elements such as rocks, tin, kaolin, bitumen, barite, hydrocarbon (coal), and gold in the country. The measured activity concentrations of natural radionuclides, mainly ^{226}Ra, ^{232}Th, and ^{40}K, in the various minerals and elements and their corresponding radiological parameters are summarized in Table S5.

Generally, radioactivity concentrations in mineral samples collected in Nigeria are low and comparable to those from other parts of the world (Ajayi and Kuforiji 2001; Fasasi et al. 2003; Balogun et al. 2003; Mokobia et al. 2006;

Ademola et al. 2008; Jibiri and Emelue 2008; Isinkaye et al. 2015), except for the phosphate rock site in Sokoto (Ogunleye et al. 2002; Gbadebo and Amos 2010; Kolo 2014) and the kaolin field in the Ifonyintedo area of Ogun state (Adagunodo et al. 2018). For example, phosphate rocks from Sokoto have a radium equivalent activity higher than the 370 Bq/kg permissible limit recommended by OECD (1979), and mineral sands from Jos Plateau showed elevated radioactivity levels above those reported for areas of high natural radioactive background (Arogunjo et al. 2009). Although most of the obtained radioactivity concentrations are low and should not pose any radiological hazards to the local population, it is recommended that periodic assessments of radioactivity levels of these mineral resources are performed, for radiological health monitoring purposes.

Radioactivity due to exploration and extraction processes

Anthropogenic activities have the potential of changing the radioactivity profile of the environment. Many exploration and extraction processes are going on in the country which may potentially alter the radioactivity levels of the environment and consequently influence the exposure to ionizing radiation. For instance, the Niger Delta region with its widespread environmental degradation has been referred to as an ecological wasteland by the United Nations Environment Program, as a result of contamination from unregulated oil and gas production in the region (Babatunde et al. 2019). The presence of huge mining activities across the northcentral states and in some parts of the southwestern states of Nigeria has also raised concerns about the environmental implications (Jibiri et al. 2009a, 2009b). Hence, research studies investigating the radioactivity levels in the environment around exploration and extraction sites of mineral resources would help to determine how far the host communities and farmlands have been impacted radiologically. Important studies in this regard have been reviewed here and the results are summarized in Table S6.

The information summarized in Table S6 suggests that radioactivity levels of Nigerian soils have been affected in some ways where anthropogenic activities are currently taking place. Although in some cases soil radioactivity levels are not higher than the world average values of 33, 45, and 420 Bq kg^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K, respectively (UNSCEAR 2000; Okeji et al. 2012; Jibiri and Esen 2013; Ibrahim et al. 2013; Jibiri and Temaugee 2013; Nwankpa 2015; Kolo et al. 2017), the obtained values are higher than the values in the undisturbed soils from the same locality. This is an indication that industrial activities may have increased the radioactivity levels in these soils. In other cases, the background radiation levels in soils of disturbed and undisturbed areas have exceeded both the world average values and the reference value of 1 mSv y^{-1} recommended by the ICRP, NCRP and CFR due to contamination by industrial activities (Dike et al. 2019; Isola et al. 2019; Osimobi et al. 2018; Nwankwo et al. 2014; Ademola and Olatunji 2013; Olise et al. 2011; Nwankwo and Akoshile 2005; Oyeyemi et al. 2017; ICRP 1999, 2019; CFR 1979; NCRP 1975). For instance, most Niger Delta areas, particularly the oil and gas production areas in the Delta state were reported to have exceeded the permissible radiation dose for the public (Jibiri and Farai 1998; Agbalagba et al. 2012; Anekwe et al. 2013). Also, the soil radioactivity levels of the northcentral region such as those at the tin mining sites in Jos Plateau, and the solid mineral (such as barite, copper, zinc, lead, tantalite, and granite) mining areas at the Nasarawa and Ilorin quarry sites in Kwara, have all exceeded the normal background radiation levels (Jibiri et al. 2009b; Aliyu et al. 2015a; Olise et al. 2010). Similar situations have been reported in the southwest region such as the Ogun and Ondo states where bitumen exploration and other industrial activities are currently being practiced (Oyeyemi and Aizebeokhai 2015; Olawale et al. 2018), and waste dumpsite in southern region (Avwiri and Olatunbosun 2014). The most important concern is the possibility of leaching of radionuclides from contaminated soils into water bodies, drainage, dust, etc., which can be transported to farm soils and subsequently get incorporated into the human food chain. When farmlands are contaminated this way, it can negatively impact agricultural practices and this could eventually result in food insecurity. Hence, it is suggested that regular monitoring, control and remediation strategies are necessary for and around exploration and extraction sites to avoid any radiation-related health consequences for workers and members of the public.

Radioactivity in local and imported commercial building materials

Radioactivity levels in building materials such as cement, concrete blocks and tiles which are made and used in different parts of the country have also been measured. The measured activity concentrations for ^{226}Ra, ^{232}Th, and ^{40}K with their corresponding radiological hazard indices have been reviewed and summarized in Table S7.

It can be concluded from the studies of radioactivity measurements in commercial building materials summarized in Table S7 that radioactivity levels higher than the world averages were found, but that this does not translate into significantly higher radiation exposures by the inhabitants (Farai and Ademola 2001; Ademola and Farai 2005; Farai and Ejeh 2006; Jibiri and Adewuyi 2008; Ademola 2009; Joel et al. 2018; Okeyode et al. 2019). The higher radioactivity levels in these building materials could be

attributed to the radioactivity levels in the raw materials from which these materials were obtained. Since the studied building materials were obtained from both local and foreign sources, thorough efforts are required to regularly monitor the radioactivity levels of commercially imported building materials, while building materials produced locally and corresponding raw materials should be monitored. Such efforts are necessary to avoid unnecessary exposure of dwellers to radiation when staying in their buildings.

Discussion and way forward

From the reviewed literature performed it is obvious that quite some studies on the natural radioactivity in Nigeria have been performed in the last 2 decades. The review shows a wide variation of natural radioactivity concentrations in environmental samples. On the one hand, the radioactivity levels measured in normal soils are well within the world averages of 33, 45, and 420 Bq kg^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K, respectively (UNSCEAR 2000). On the other hand, however, soils from certain areas have shown a rather high background radiation levels, sometimes even far higher values compared to the corresponding world averages (Farai and Jibiri 2000; Ajayi and Achuka 2009; Alatise et al. 2008; Jibiri et al. 2009a; Umar et al. 2012; Olise et al. 2014; Oyeyemi and Aizebeokhai 2015; Oyeyemi et al. 2017). The radionuclide concentrations measured in samples from different areas reflect the different geological structures of those areas, their geographical peculiarities, soil types and climatic conditions (Abba et al. 2017). Soils high in ^{238}U have been associated with the widespread occurrence of igneous rocks whereas those high in ^{232}Th have been found mostly in soils that originated from sedimentary rocks (Guidotti et al. 2015). This may explain why the rocks in Sokoto show higher ^{226}Ra (daughter of ^{238}U) than ^{232}Th concentrations (Ogunleye et al. 2002; Arogunjo et al. 2009; Joshua et al. 2009), and the same goes for rocks from the southern area (Joshua et al. 2009). In contrast, investigations carried out on northeastern and northcentral rocks revealed higher ^{232}Th than ^{238}U concentrations (Ademola and Ayeni 2010; Maxwell et al. 2014; Arabi et al. 2016), which is consistent with a high content of ^{232}Th in the rocks obtained from Ondo state in southwestern Nigeria (Ademola and Ayeni 2010). This implies that the rock type from which the soil formed played a major role in the soil's radioactivity level. Geologically, half of Nigeria is based on crystalline rocks or basement complexes (composed of metamorphic and igneous rocks such as migmatites, granites and gneisses) while the other half is based on sedimentary rocks (Jibiri et al. 2009a). Based on the reported studies, typical Nigerian soil radioactivity levels measured for some high background radiation areas ranged between 65 and 163 Bq kg^{-1} (^{226}Ra), between 184 and 451 Bq kg^{-1} (^{232}Th), and between 411 and 1,062 Bq kg^{-1} (^{40}K) (Olomo et al. 1994; Jibiri et al. 2009a; Ademola et al. 2014; Ademola and Ademonehin 2010; Abba et al. 2018). The radioactivity levels are even higher for sediments in some riverine areas and reach values of up to 484 (^{226}Ra), 812 (^{238}U), 840 (^{232}Th), and 3,760 Bq kg^{-1} (^{40}K) (Isinkaye and Emelue 2015; Babatunde et al. 2015). These values are comparable to those present in some known high background radiation areas such as, for example, the Odisha coast in India (where corresponding values of 350, 2,825, and 180 Bq kg^{-1} for ^{238}U, ^{232}Th, and ^{40}K, were reported, respectively) (Mohanty et al. 2004). Figure 1 below is a map of Nigeria showing the variation of background radiation in different areas as deduced in the present review. As seen in Fig. 1, Jos Plateau in the northcentral and Abeokuta—Ogun in the southwestern part of the country are considered as high background radiation areas. The distribution pattern shown in Fig. 1 is due to the radionuclide concentrations measured in either rock or sediment samples taken from different areas in Nigeria.

Sometimes, high natural radiation levels and release of artificial radionuclides (such as ^{137}Cs) into the environment are attributable to anthropogenic activities involving the exploitation of mineral resources or use of nuclear materials in operations (Akinloye et al. 2012; Ademola and Obed 2012; Usikalu et al. 2014; Onwuka and Ononugho 2019). Nigeria is rich in mineral deposits and these minerals are widely distributed across different regions of the country. The oil-rich Niger Delta region of Nigeria has been known for a long time for extensive exploration and extraction of crude oil and gas, while the northcentral states (Jos Plateau, Niger, and Nasarawa) are among the areas where solid minerals have been mined for a century. This review showed that the radioactivity levels in these areas vary widely. For example, samples from dumped tailing and mining sites in northcentral states have shown very high radioactivity concentrations of up to 27,240 (^{238}U), 42,480 (^{232}Th), and 670 Bq kg^{-1} (^{40}K), which are higher than those reported from high normal background radiation areas in other parts of the world (Olise et al. 2010, 2014; Aliyu et al. 2015a). Because of such high values, some authors have expressed worries about the human and environmental health in these areas (Oramah et al. 2015; Aliyu et al. 2015a, 2015b; Omotehinse and Ako 2019). However, since high radioactivity levels do not necessarily imply direct radiological consequences from the radiation protection point of view, conversion of radionuclide concentration to effective doses for the population is necessary for radiological impact assessment. The doses estimated from the corresponding radioactivity measurements have been reviewed and are included in the summary Tables (Tables S2–S7). As proposed by the ICRP, 1 Sv of effective dose roughly implies a 5% probability of dying from cancer at some time in life (ICRP 2007). Doses obtained from

most of the areas reviewed here are not higher than those obtained in normal background radiation areas across the world (Ajanaku et al. 2018; Agbalagba et al. 2016a; Olarinoye et al. 2010; Sohrabi 2013), but there are a few exceptions where annual effective doses have been reported higher than 1 mSv y^{-1} reference value for the general public (Ibeanu 2003; Agbalagba et al. 2016b). The high doses in these areas can be linked to the contamination of the environment due to heavy human exploitation and extraction activities. This is an indication that inhabitants of these areas may be experiencing some increased radiological health risks now or in the future. Since studies quantifying any effects of ionizing radiation on human or non-human biota are still very sparse in the country, epidemiological studies are needed to address any health effects of long-term exposure to elevated levels of natural radioactivity across the country, especially now that studies have shown that cancer cases are currently increasing among the people in the country (Jedy–Agba et al. 2012).

The present review shows that very few studies have been conducted on radioactivity levels in surface and underground waters which are sources of drinking water for most Nigerians. Ingestion of radionuclides through drinking water can serve as a major pathway to internal radiation exposure. As mentioned earlier in this review, the radioactivity levels in water available for domestic and industrial purposes in the country have generated some concerns among the researchers who have worked on these water samples. For instance, studies on water used by people in areas such as Ile-Ife (Tchokossa et al. 1999), Ondo state (Adebayo and Akinnawo 2017; Ajayi and Adesida 2009), Ogun state (Ajayi and Achuka 2009), Federal Capital City (Umar et al. 2012), Kano state (Bello et al. 2020), Kwara state (Nwankwo 2013), Ogbomoso (Oni and Adagunodo 2019) and in Niger Delta region (Agbalagba and Onoja 2011; Onunogbo et al. 2017; Agbalagba et al. 2021), have shown higher radium concentrations as compared to the range of values observed worldwide (0.01 to 0.1 Bq l^{-1}) (Iyengar 1990; Dissanayake and Chandrajith 2009). This should warrant urgent action as ^{226}Ra is one of the radionuclides that may compromise human health, due to its long half-life and α-emission. Once ^{226}Ra is ingested in the body, critical target organs where it is accumulated due to its biokinetics are bones and teeth. Generally, ^{226}Ra is absorbed by metabolic processes instead of calcium, and may cause the splitting of chemical bonds in organic and mineral parts due to ionizing events (Aghamiri et al. 2006).

In addition, it is obvious that gamma-spectrometric approaches involving HPGe, NaI(Tl), and radiation survey meters are the analytical techniques of choice, and are generally acceptable for ^{238}U, ^{232}Th, and ^{40}K radionuclide measurements. However, due to the rather high detection limits of the detectors used in these approaches, other radionuclides of importance such as ^{235}U, ^{234}Th, ^{210}Pb and cosmogenic radionuclides (such as ^{7}Be), have been considered only by a few authors. It is important to note that ^{210}Pb and ^{210}Po, in particular, contribute to the exposure of humans to natural radiation. These radionuclides can be absorbed from the soil by plant roots or deposited on the plant shoots from the atmosphere (Persson and Holm 2014). Therefore, they should be considered in environmental radioactivity measurements, particularly in areas where prolonged industrial exploration and extraction processes have been reported. In a recent review on the status of radioactivity in the oil and gas producing areas of the Niger delta (Babatunde et al. 2019), and in the tin mining area of Jos Plateau (Aliyu et al. 2015b), it was shown that various anthropogenic activities have resulted in an increase of radionuclide levels in these areas, with the potential of some health consequences among the population. It is, therefore, suggested that the new analytical methods involving the use of advanced detectors such as Broad Energy High Purity Germanium (BEGe) and Low Energy Purity Germanium (LEGe) detectors, be encouraged for the determination of radionuclides emitting low energy photons such as ^{234}Th and ^{210}Pb present in the decay series of ^{238}U. Such studies, as have been reported elsewhere, will allow a better study of radioactive equilibrium between the radionuclides in the ^{238}U decay series (such as ^{226}Ra and ^{210}Pb as well as its short-lived alpha decay product ^{210}Po) (Anagnostakis 2015).

Finally, the development of predictive radioecological models for radionuclide levels in the environment can be a good way to study environmental radioactivity for an assessment of radiation-induced exposures and health effects.

Conclusion

Environmental radioactivity measurements are very important from the human and environmental protection point of view. For example, baseline radiation data are useful in decision making processes relating to land use, environmental conservation, agriculture, and public health. Where such data are not available, adequate monitoring by regulatory agencies for human radiation exposure and the development of policies will be difficult, and it is often impossible to detect any changes in radiation levels due to anthropogenic activities. In the present paper, studies were reviewed that were conducted on environmental radioactivity measurements in Nigeria. Thus, this review provides the radiation data of different environments in Nigeria in a single document. The review showed that the background radioactivity levels of most Nigerian soils fall within the world averages of 33, 45, and 420 Bq kg^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K, respectively, as reported by (UNSCEAR 2000), whereas a few high background radiation areas such as Abeokuta in

the southwest and Jos in the northcentral show values comparable to those of high background radiation areas in other regions of the world such as at the Odisha coast in India (where measured values were reported as 350, 2,825, and 180 Bq kg^{-1} for $^{238}U/^{226}Ra$, ^{232}Th, and ^{40}K, respectively). It is expected that this review will be found useful by decision makers, and will support future research studies on environmental radioactive contamination among researchers in Nigeria.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00411-022-00993-3.

Acknowledgements The authors express their gratitude to Research Center of Advanced Materials, King Khalid University, Saudi Arabia, for support (award number KKU/RCAMS/22).

Declaration

Conflict of interest The authors declare that they have no conflict of interest.

References

Abba HT, Hassan WMSW, Saleh MA, Aliyu AS, Ramli AT (2017) Terrestrial gamma radiation dose (TGRD) levels in northern zone of Jos Plateau, Nigeria: statistical relationship between dose rates and geological formations. Radiat Phys Chem 140:167–172

Abba TH, Hassan WMSW, Saleh MA (2018) Evaluation of environmental natural radioactivity levels in soil and groundwater of Barkin Ladi, Plateau state, Nigeria. Malays J Fundam Appl Sci 14(3):338–342

Adagunodo TA, George AI, Ojoawo IA, Ojesanmi K, Ravisankar R (2018) Radioactivity and radiological hazards from a kaolin mining field in Ifoyintedo, Nigeria. MethodsX 5:362–374

Adebayo OC, Akinnawo OO (2017) Assessment of radiological hazard of natural radioactivity in drinking water in Ondo Nigeria. J Sci Res Rep 17(5):1–11

Ademola JA (2008) Exposure to high background radiation level in the tin mining area of Jos Plateau, Nigeria. J Radiol Prot 28:93–99

Ademola JA (2009) Natural radioactivity and hazard assessment of imported ceramic tiles in Nigeria. Afr J Biomed Res 12(3):161–165

Ademola JA, Ademonehin S (2010) Radioactivity concentrations and dose assessment for bitumen and soil samples around a bituminous deposit in Ondo state Nigeria. Radioprotection 45(3):359–368

Ademola JA, Atare EE (2010) Radiological assessment of natural radionuclides in soil within and around crude oil flow and gas compression stations in the Niger Delta Nigeria. Radioprotection 45(2):219–227

Ademola JA, Ayeni AA (2010) Measurement of natural radionuclides and dose assessment of granites from Ondo state Nigeria. Radioprotection 45(4):513–521

Ademola JA, Farai IP (2005) Annual effective dose due to natural radionuclides in building blocks in eight cities of southwestern Nigeria. Radiat Prot Dosim 114(4):524–526

Ademola JA, Farai IP (2006) Gamma activity and radiation dose in concrete building blocks used for construction of dwellings in Jos Nigeria. Radiat Prot Dosim 121(4):395–398

Ademola AK, Obed RI (2012) Gamma radioactivity levels and their corresponding external exposure of soil samples from tantalite mining areas of Oke-Ogun Southwestern Nigeria. Radioprotection 47(2):243–252

Ademola JA, Olatunji MA (2013) Evaluation of NORM and dose assessment in an aluminium industry in Nigeria. World J Nucl Sci Technol 3:150–154

Ademola AK, Hammed OS, Adejumobi CA (2008) Radioactivity and dose assessment of marble samples from Igbeti mines Nigeria. Radiat Prot Dosim 132(1):94–97

Ademola AK, Bello AK, Adejumobi AC (2014) Determination of natural radioactivity and hazard in soil samples in and around gold mining area of Itagunmodi, south-western Nigeria. J Radiat Res Appl Sci 7:249–255

Agbalagba EO, Onoja RA (2011) Evaluation of natural radioactivity in soil, sediment and water samples of Niger Delta (Biseni) flood plain lakes, Nigeria. J Environ Radioactiv 102:667–671

Agbalagba EO, Avwiri GO, Chad-Umoreh YE (2012) γ-spectroscopy measurement of natural radioactivity and assessment of radiation hazard indices in soil samples from oil fields environment of Delta state, Nigeria. J Environ Radioactiv 109:64–70

Agbalagba EO, Osimobi CO, Avwiri GO (2016a) Excess lifetime cancer risk from measured background ionizing radiation levels in active coal mines sites and environs. Environ Processes. https://doi.org/10.1007/s40710-016-0173-z

Agbalagba EO, Avwiri GO, Ononugbo CP (2016b) GIS mapping of impact of industrial activities on the terrestrial background ionizing radiation levels of Ughelli metropolis and its environs Nigeria. Environ Earth Sci 75:1425

Agbalagba EO, Egarievwe SU, Odesiri-Eruteyan EA, Drabo ML (2021) Evaluation of gross alpha and gross beta radioactivity in crude oil polluted soil, sediment and water in the Niger Delta region of Nigeria. J Environ Protect 12:526–546

Aghamiri SMR, Ghorbani Z, Darafsheh A, Torabzadeh H, Fathivand AA, Minuchehr A, Jalinoos A (2006) ^{226}Ra concentration in the teeth of habitants of areas with high level of natural radioactivity in Ramsar. J Environ Radioactiv 89:212–218

Ajanaku O, Ilori AO, Ibitola GA, Faturobi OB (2018) Assessment of natural radioactivity and associated dose rates in surface soils around Oluwa Glass industry Environments, Igbokoda, Ondo State Southwestern Nigeria. Phys Sci Int J 20(3):1–13

Ajayi IR (2008) Background radioactivity in the sediments of some rivers and streams in Akoko, southwestern Nigeria and their radiological effects. Res J Appl Sci 3(3):183–188

Ajayi OS (2009) Measurement of activity concentrations of ^{40}K, ^{226}Ra and ^{232}Th for assessment of radiation hazards from soils of the southwestern region of Nigeria. Radiat Environ Bioph 48:323–332

Ajayi OS, Achuka J (2009) Radioactivity in drilled and dug well drinking water of Ogun State Southwestern Nigeria and consequent dose estimates. Radiat Prot Dosim 135(1):54–63

Ajayi OS, Adesida G (2009) Radioactivity in some sachet drinking water samples produced in Nigeria Iran. J Radiat Res 7(3):151–158

Ajayi IR, Kuforiji OO (2001) Natural radioactivity measurements in rock samples of Ondo and Ekiti states in Nigeria. Radiat Meas 33:13–16

Ajayi OS, Ibikunle SB, Ojo TJ (2008) An assessment of natural radioactivity of soils and its external radiological impact in southwestern Nigeria. Health Phys 94(6):558–566

Ajayi TR, Torto N, Tchokossa P, Akinlua A (2009) Natural radioactivity and trace metals crude oils: implication for health. Environ Geochem Health 31:61–69

Akinloye MK, Isola GA, Oladapo OO (2012) Investigation of natural gamma radioactivity levels and associated dose rates from surface soils in ore metropolis, Ondo State Nigeria. Environ Nat Resour Res 2(1):140–145

Aladeniyi K, Olowookere C, Oladele BB (2019) Measurement of natural radioactivity and radiological hazard evaluation in the soil samples collected from Owo, Ondo state, Nigeria. J Radiat Res Appl Sci 12(1):200–209

Alatise OO, Babalola IA, Olowofela JA (2008) Distribution of some natural gamma-emitting radionuclides in the soils of the coastal areas of Nigeria. J Environ Radioactiv 99:1746–1749

Aliyu AS, Ramli AT, Saleh MA (2013) Nigeria electricity crisis: power generation capacity expansion and environmental ramifications. Energy 16:354–367

Aliyu AS, Ibrahim U, Akpa CT, Garba NN, Ramli AT (2015a) Health and ecological hazards due to natural radioactivity in soil from mining areas of Nasarawa state Nigeria. Isot Environ Health Stud 51(3):448–468

Aliyu AS, Mousseau TA, Ramli AT, Bununu YA (2015b) Radioecological impacts of tin mining. Ambio. https://doi.org/10.1007/s13280-015-0677-1

Amakom CM, Jibiri NN (2010) Chemical and radiological risk assessment of uranium in borehole and well water in the Odeda area, Ogun state Nigeria. Int J Phys Sci 5(7):1009–1014

Anagnostakis MJ (2015) Environmental radioactivity measurements and applications– difficulties, current status and future trends. *J Environ Radioactiv*: In–press

Anekwe UL, Avwiri GO, Agbalagba EO (2013) Assessment of gamma radiation levels in selected oil spilled areas in Rivers state Nigeria. Energy Sci Technol 5(1):33–37

Arabi AS, Futua II, Dewu BBM, Kwaya MY, Kurowska E, Muhammad AM, Garba ML (2016) NORM, radon emanation kinetics and analysis of rocks-associated radiological hazards. Environ Earth Sci 75:689

Arogunjo AM, Hollriegl V, Giussani A, Leopold K, Gerstmann U, Veronese I, Oeh U (2009) Uranium and thorium in soils, mineral sands, water and food samples in a tin mining area in Nigeria with elevated activity. J Environ Radioactiv 100:232–240

Asaduzzaman Kh, Mannan F, Khandaker MU, Farook MS, Elkezza A, Amin YB, Sharma S, Abu Kassim HB (2015) Assessment of natural radioactivity levels and potential radiological risks of common building materials used in Bangladeshi dwellings. PLoS ONE 10(10):1–16

Avwiri GO, Olatubosun SA (2014) Assessment of environmental radioactivity in selected dumpsites in Port Harcourt, rivers State, Nigeria. Int J Sci Technol Res 3(4):263–269

Babatunde BB, Sikoki FD, Hart I (2015) Human health impact of natural and artificial radioactivity levels in the sediments and fish of bonny estuary, Niger Delta, Nigeria. Challenges 6:244–257

Babatunde BB, Sikoki FD, Avwiri GO, Chad-Umoreh YE (2019) Review of the status of radioactivity profile in the oil and gas producing areas of the Niger Delta region of Nigeria. J Environ Radioactiv 202:66–73

Balogun FA, Mokobia CE, Fasasi MK, Ogundare FO (2003) Natural radioactivity associated with bituminous coal mining in Nigeria. Nucl Instrum Methods Phys Res A 505:444–448

Bello S, Nasiru R, Garba NN, Adeyemo DJ (2020) Annual effective dose associated with radon, gross alpha and gross beta radioactivity in drinking water from gold mining areas of Shanono and Bagwai, Kano state Nigeria. Microchem J 154:104551

Beretka J, Matthew PJ (1985) Natural radioactivity of Australian building materials, industrial wastes and by-products. Health Phys 48(1):87–95

CFR (1979) Standards for the protection against radiation. United States Nuclear Regulatory Commission Rules and Regulations. Code of Federal Regulations. Title 10, part 20. Washington DC, USNRC

Dike CG, Oladele BO, Olubi OE, Ife-Adediran OO, Aderibigbe A (2019) Ecological and radiological hazards due to natural radioactivity and heavy metals in soils of some selected mining sites in Nigeria. Human Ecolog Risk Assess. https://doi.org/10.1080/10807039.2019.1585182

Dissanayake CB, Chandrajith R (2009) Introduction to Medical Geology. Springer, Netherlands

Doyi IN, Essumang DK, Dampare SB, Duah D, Ahwireng AF (2017) Evaluation of radionuclides and decay simulation in a terrestrial environment for health risk assessment. Sci Rep 7:16537

Eke BC, Jibiri NN, Anusionwu BC, Orji CE, Emelue HU (2015) Baseline measurements of natural radioactivity in soil samples from the Federal University of Technology, Owerri, South-East Nigeria. Br J Appl Sci Technol 5(2):142–149

EC (European Commission) (1999) Radiological protection principles concerning the natural radioactivity of building materials. Radiation protection report No 112, Directorate General for Environment, Nuclear Safety and Civil protection

Farai IP, Ademola JA (2001) Population dose due to building materials in Ibadan Nigeria. Radiat Prot Dosim 95(1):69–73

Farai IP, Ejeh JE (2006) Radioactivity concentrations in common brands of cement in Nigeria. Radioprotection 41(4):455–462

Farai IP, Jibiri NN (2000) Baseline studies of terrestrial outdoor gamma dose rate levels in Nigeria. Radiat Prot Dosim 88(3):247–254

Fasasi MK, Oyawale AA, Mokobia CE, Tchokossa P, Ajayi TR, Balogun FA (2003) Natural radioactivity of the tar-sand deposits of Ondo state, Southwestern Nigeria. Nucl Instrum Methods Phys Res A 505:449–453

Gbadebo AM, Amos AJ (2010) Assessment of radionuclide pollutants in bedrock and soils from Ewekoro cement factory Southwest Nigeria. Asian J Appl Sci 3(2):135–144

Guidotti L, Carini F, Rossi R, Gatti M, Cenci RM, Beone GM (2015) Gamma-spectrometric measurement of radioactivity in agricultural soils of the Lombardia region, northern Italy. J Environ Radioactiv 142:36–44

Ibeanu IGE (2003) Tin mining and processing in Nigeria: cause for concern? J Environ Radioact 64:59–66

Ibrahim U, Akpa TC, Daniel IH (2013) Assessment of radioactivity concentration in soil of some mining areas in central Nasarawa state Nigeria. Sci World J 8(2):7–12

ICRP (1991) Recommendations of the International Commission on Radiological Protection, vol 21, No 1 – 3, publication 60

ICRP (1994) Protection against Rn-222 at home and at work. Oxford: Publication No. 65; Ann ICRP. Pergamon 23:2

ICRP (1999) The 1995 – 99 recommendation of the International Commission on Radiological Protection publication 76. Pergamon Press

ICRP (2007) The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Annl ICRP 37 (2–4)

ICRP (2019) Radiological Protection from Naturally Occurring Radioactive Material (NORM) in industrial processes. ICRP Publication 142. Annl ICRP 48 (4)

Isinkaye OM (2008) Radiometric assessment of natural radioactivity levels of bituminous soil in Agbabu, southwest Nigeria. Radiat Meas 43:125–128

Isinkaye OM, Emelue HU (2015) Natural radioactivity measurements and evaluation of radiological hazards in sediment of Oguta Lake, South East Nigeria. J Radiat Res Appl Sci 1:1–11

Isinkaye OM, Jibiri NN, Olomide AA (2015) Radiological health assessment of natural radioactivity in the vicinity of Obajana cement factory Northcentral Nigeria. J Med Phys 40(1):52–59

Isola GA, Oni OM, Akinloye MK, Awodugba AO (2015) Determination of absorbed dose rate and effective dose equivalent due

to natural radionuclide present in soil in Oyo and Osun state, South-western Nigeria. Int J Res Appl, Nat Soc Sci 3(3):27–32
Isola GA, Akinloye MK, Amuda DB, Ayanlola PS, Fajuyigbe A (2019) Assessment and evaluation of enhanced levels of naturally occurring radionuclide materials due to gold mining in soil samples obtained from Iperindo, Osun State, Southwestern Nigeria. Int J Sci Eng Res 10(9):1647–1657
ITB/CLOR (1995) Institute of Building Technology and the Central Laboratory for Radiological Protection, Building Materials, Warszawa, , Poland, ITB and CLOR, Instruction number 234: PI–03–194; http://www.Clor-waw-pl/z-2/EngBuilding.htm
Iyengar MAR (1990) The natural distribution of radium: the environmental behaviour of radium. In: Technical Reports Series. International Atomic Energy Agency (IAEA), Vienna 1990:59–128
Jedy-Agba E, Curado MP, Ogunbiyi O, Oga E, Fabowale T, Igbinoba F, Osubor G, Otu T et al (2012) Cancer incidence in Nigeria: a report from population-based cancer registries. Cancer Epidemiol 36(5):271–278
Jibiri NN, Adewuyi GO (2008) Radionuclide contents and physic-chemical characterization of solid waste and effluent samples in some selected industries in the city of Lagos Nigeria. Radioprotection 43(2):203–212
Jibiri NN, Emelue HU (2008) Soil radionuclide concentrations and radiological assessment in and around a refining and petrochemical company in Warri, Niger Delta Nigeria. J Radiol Prot 28:361–368
Jibiri NN, Esen NU (2013) Radionuclide contents and radiological risk to the population due to raw materials from the mining sites of quality ceramic and pottery industries in Akwa Ibom Nigeria. Radioprotection 46(1):75–87
Jibiri NN, Farai IP (1998) Assessment of dose rate and collective effective dose equivalent due to terrestrial gamma radiation in the city of Lagos Nigeria. Radiat Prot Dosim 76(3):191–194
Jibiri NN, Temaugee ST (2013) Radionuclide contents in raw minerals and soil samples and the associated radiological risk from some mining sites in Benue state Northcentral Nigeria. Int J Sci Eng Res 4(7):2392–2400
Jibiri NN, Alausa SK, Farai IP (2009a) Radiological hazard indices due to activity concentrations of natural radionuclides in farm soils from two high background radiation areas in Nigeria. Int J Low Radiat 6(2):79–94
Jibiri NN, Alausa SK, Farai IP (2009b) Assessment of external and internal doses due to farming in high background radiation areas in old tin mining localities in Jos-Plateau Nigeria. Radioprotection 44(2):139–151
Joel ES, Maxwell O, Adewoyin OO, Ehi-Eromosele CO, Embong Z, Oyawoye F (2018) Assessment of natural radioactivity in various commercial tiles used for building purposes in Nigeria. MethodsX 5:8–19
Joshua EO, Ademola JA, Akpanowo MA, Oyebanjo OA, Olorode DO (2009) Natural radionuclides and hazards of rock samples collected from Southeastern Nigeria. Radiat Meas 44:401–404
Khandaker MU, Jojo PJ, Kassim HA, Amin YM (2012) Radiometric analysis of construction materials using hpge gamma-ray spectrometry. Radiat Prot Dosim 152:33–37
Khandaker MU, Wahib NB, Amin YM, Bradley DA (2013) Committed effective dose from naturally occurring radionuclides in shellfish. Radiat Phys Chem 88:1–8
Kolo MT (2014) Natural radioactivity and environment risk assessment of Sokoto phosphate rock, Northwest Nigeria. Afr J Environ Sci Technol 8(9):532–538
Kolo MT, Amin YM, Khandaker MU, Abdullah WHB (2017) Radionuclide concentrations and excess lifetime cancer risk due to gamma radioactivity in tailing enriched soil around Maiganga coal mine Northeast Nigeria. Int J Radiat Res 15(1):71–80
Maxwell O, Wagiran H, Ibrahim N, Lee SK, Embong Z, Ugwuoke PE (2014) Natural radioactivity and geological influence on subsurface layers at Kubwa and Gosa area of Abuja North-central Nigeria. J Radioanal Nucl 1:1. https://doi.org/10.1007/s10967-014-3442-1
Mohanty AK, Sengupta D, Das SK, Vijayan V, Saha SK (2004) Natural radioactivity in the newly discovered high background radiation area on the Eastern Coast of Orissa, India. Radiat Meas 38:153–165
Mokobia CE, Adebiyi FM, Akpan I, Olise FS, Tchokossa P (2006) Radioassay of prominent Nigerian fossil fuels using gamma and TXRF spectroscopy. Fuel 85:1811–1814
NCRP (1975) Natural background radiation in the United States. Recommendation of the National Council of radiation and measurements 45
Nwankpa AC (2015) Evaluation of background radioactivity in Ogbete coal mine dumpsites in Enugu Nigeria. Int J Sci Engr Res 6(9):155–160
Nwankwo LI (2013) Determination of natural radioactivity in groundwater in Tanke-Ilorin Nigeria. West Afr J Appl Geol 21(1):111–119
Nwankwo LI, Akoshile CO (2005) Monitoring of external background radiation level in Asa Dam industrial area of Ilorin, Kwara state Nigeria. J Appl Sci Environ Manag 9(3):91–94
Nwankwo LI, Akoshile CO, Alabi AB, Ojo OO, Ayodele TA (2014) Environmental ionizing radiation survey of quarry sites in Ilorin industrial area Nigeria. Niger J Basic Appl Sci 22(1&2):1–4
Obed RI, Farai IP, Jibiri NN (2005) Population dose distribution due to soil radioactivity concentration levels in 18 cities across Nigeria. J Radiol Prot 25:305–312
OECD (1979) Exposure to radiation from the natural radioactivity in building materials. *Report by a group of experts of the OECD Nuclear Energy Agency*. Paris, France: Organization for Economic Cooperation and Development
Ogunleye PO, Mayaki MC, Amapu IY (2002) Radioactivity and heavy metal composition of Nigerian phosphate rocks: possible environmental implications. J Environ Radioactiv 62:9–48
Okeji MC, Agwu KK, Idigo FU (2012) Natural radioactivity in cultivated land in the vicinity of a phosphate fertilizer plant in Nigeria. Radiat Phys Chem 81:1823–1826
Okeyode IC, Oladotun IC, Alatise OO, Bada BS, Makinde V, Akinboro FG, Mustapha AO, Al-Azmi D (2019) Indoor gamma dose rates in the high background radiation area of Abeokuta, South Western Nigeria. J Radiat Res Appl Sci 12(1):72–77
Olarinoye IO, Sharifat I, Baba-Kutigi AN, Kolo MT, Aladeniyi K (2010) Measurement of background gamma radiation levels at two tertiary institutions in Minna Nigeria. J Appl Sci Environ Manage 14(1):59–62
Olatunji MA, Uwatse OB, Khandaker MU, Amin YM, Faruq G (2014) Radiological study on newly developed composite corn advance lines in Malaysia. Phys Scr 89:125002
Olawale IA, Adefisoye OP, Catherine BS (2018) Estimation of natural radionuclide concentrations and heavy metal contents due to bitumen exploitation at Gbeledu-Loda, Ode-Irele, Ondo State, Southwestern Nigeria. Asian J Phys Chem Sci 6(4):1–10
Olise FS, Owoade OK, Olaniyi HB, Obiajunwa EI (2010) A Complimentary tool in the determination of activity concentrations of naturally occurring radionuclides. J Environ Radioactiv 101:910–914
Olise FS, Owoade OK, Olaniyi HB (2011) Radiological indices of technologically enhanced naturally occurring radionuclides: a PIXE approach. J Radiol Prot 31:255–264
Olise FS, Oladejo OF, Almeida SM, Owoade OK, Olaniyi HB, Freitas MC (2014) Instrumental neutron activation analyses of uranium and thorium in samples from tin mining and processing sites. J Geochem Explor 142:36–42

Olomo JB, Akinloye MK, Balogun FA (1994) Distribution of gamma-emitting natural radionuclides in soils and water around nuclear research establishments, Ile-Ife, Nigeria. Nucl Instrum Methods Phys Res A 353:553–557

Omotehinse AO, Ako BD (2019) The environmental implications of the exploration and exploitation of solid minerals in Nigeria with a special focus on Tin in Jos and coal in Enugu. J Sustain Min 18:18–24

Oni EA, Adagunodo TA (2019) Assessment of radon concentration in groundwater within Ogbomoso SW Nigeria. J Phys:conf Series 1299:01209851

Ononugbo CP, Avwiri GO, Agbalagba EO (2017) Radioactive pollution and excess lifetime cancer risk due to gamma exposure of soil and groundwater around open landfills in River State Nigeria. Canadian J Pure Appl Sci 11(1):4121–4130

Onwuka M, Ononugbo CP (2019) Radiometric survey of granitic quarry site of Ebonyi State Nigeria. Adv Res 20(2):1–9

Oramah IT, Richards JP, Summers R, Garvin T (2015) Artisanal and small-scale mining in Nigeria: Experiences from Niger, Nasarawa and Plateau states. Extr Ind Soc 2:694–703

Osimobi JC, Avwiri GO, Agbalagba EO (2018) Radiometric and radiogenic heat evaluation of natural radioactivity in soil around solid minerals mining environment in southeastern Nigeria. Environ Processes. https://doi.org/10.1007/s40710-018-0336-1

Oyeyemi KD, Aizebeokhai AP (2015) Geogenic radiological impact assessment of soil samples collected from parts of Sagamu Southwestern Nigeria. Indian J Nat Sci 6(33):1029–10308

Oyeyemi KD, Usikalu MR, Aizebeokhai AP, Achuka JA, Jonathan O (2017) Measurements of radioactivity levels in part of Ota Southwestern Nigeria: Implications for radiological hazards indices and excess lifetime cancer-risks. J Phys: Conf Series 852:012042

Persson BRR, Holm E (2014) ^{7}Be, ^{210}Pb and ^{210}Po in the surface air from the Arctic to Antarctica. J Environ Radioactiv 1:1–11

Shuaibu HK, Khandaker MU, Alrefae T, Bradley DA (2017) Assessment of natural radioactivity and gamma-ray dose in monazite rich black Sand Beach of Penang Island Malaysia. Mar Pollut Bull 119(1):423–428

Sohrabi M (2013) World high background natural radiation areas: need to protect public from radiation exposure. Radiat Meas 50:166–171

Tchokossa P, Olomo JB, Osibote OA (1999) Radioactivity in the community water supplies of Ife-Central and Ife-East local government areas of Osun state, Nigeria. Nucl Instrum Methods Phys Res A 422:784–789

U.S. Environmental Protection Agency (USEPA) (2000) Washington DC, vol 65, pp 76708 – 76753

Umar AM, Onimisi MY, Jonah SA (2012) Baseline measurement of natural radioactivity in soil, vegetation and water in the industrial of the Federal Capital Territory (FCT) Abuja Nigeria. Br J Appl Sci Technol 2(3):266–274

UNSCEAR (United Nations on Scientific Committee on the Effects of Atomic Radiation) (1982) Ionizing radiation: Sources and Biological Effects. Report to the General Assembly with Annexes. United Nations, NY

UNSCEAR (United Nations on Scientific Committee on the Effects of Atomic Radiation) (1988) Sources and effects of ionizing radiation. Report to the General Assembly with Annexes. New York: United Nations

UNSCEAR (United Nations on Scientific Committee on the Effects of Atomic Radiation) (1993) Sources and effects of ionizing radiation. Report to the General Assembly with Annexes. United Nations, NY, USA

UNSCEAR (United Nations on Scientific Committee on the Effects of Atomic Radiation) (1998) Sources and effects of ionizing radiation. Report to the General Assembly with Annexes. United Nations, NY, USA

UNSCEAR (United Nations on Scientific Committee on the Effects of Atomic Radiation) (2000) Sources and effects of ionizing radiation. Report to the General Assembly with scientific Annexes. United Nations: NY, USA

Usikalu MR, Akinyemi ML, Achuka JA (2014) Investigation of radiation levels in soil samples collected from selected locations in Ogun State, Nigeria. IERI Procedia 9:156–161

WHO (2008) Guidelines for drinking water policy. In: incorporating the 1st and 2nd Agenda, third ed., vol. 1. World Health Organization, Genera, Switzerland. Recommendation

WHO (2011) Guidelines for drinking water quality, 4th edn. World Health Organization, Geneva, Switzerland, pp 211–221